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IMPACT BENDING PROPERTIES OF GLUBAM AND SPF

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This study investigates the impact bending properties of two types of glued laminated bamboo (glubam), namely thick-strip (G1) and thin-strip (G2), in comparison with spruce-pine-fir (SPF) timber. Pendulum impact tests were conducted to evaluate impact toughness and dynamic modulus of rupture (MOR), considering the anisotropic nature of glubam by applying loads along different directions. Results indicate that G1 specimens exhibited superior impact toughness and dynamic MOR compared to G2 and SPF. The failure modes were significantly influenced by loading direction, with X-axis loading causing delamination and Z-axis loading leading to fiber pull-out. SPF demonstrated the lowest impact resistance. The findings provide valuable insights for optimizing hybrid cross-laminated bamboo-timber (CLBT) composites in structural applications, highlighting the potential of bamboo-based materials as sustainable alternatives to conventional wood.

ХАРАКТЕРИСТИКИ УДАРНОГО ИЗГИБА КЛЕЕНОГО БАМБУКА (GLUBAM) И ДРЕВЕСИНЫ ХВОЙНЫХ ПОРОД (SPF)

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В данном исследовании изучаются характеристики ударного изгиба двух типов клееного ламинированного бамбука (glubam) – из толстых полос (G1) и тонких полос (G2) – в сравнении с древесиной хвойных пород (SPF). Для оценки ударной вязкости и динамического модуля упругости при изгибе (MOR) были проведены испытания на маятниковом копре. С учетом анизотропной природы клееного бамбука нагрузка прикладывалась в различных направлениях. Результаты показывают, что образцы G1 обладают более высокой ударной вязкостью и динамическим модулем упругости по сравнению с G2 и SPF. На характер разрушения существенное влияние оказало направление нагружения: нагрузка вдоль оси X вызывала расслоение, а вдоль оси Z – вырыв волокон. Древесина SPF продемонстрировала самую низкую ударную прочность. Полученные результаты дают ценную

информацию для оптимизации гибридных перекрестно-клееных композитов из бамбука и древесины (CLBT) в строительных конструкциях, подчеркивая потенциал материалов на основе бамбука как экологически устойчивой альтернативы традиционной древесине».

Ключевые слова: ударная вязкость, динамический предел прочности, клееный бамбук (glubat), древесина SPF, анизотропия, перекрестно-клееная бамбуковая древесина (CLBT).

1. Introduction

With the increasing attention on the eco-friendly materials, bamboo- and wood-based composites are being considered as viable alternatives (Huang et al. 2019; Sotayo et al. 2020; Xiao 2022; Xiao et al. 2013). Bamboo and wood have the properties of lightweight, high strength, low-carbon footprint in many developing countries (Food and Agriculture Organization of the United Nations 2020). The author's group developed the glued laminated bamboo (glubat) (Xiao et al. 2008). To expand the application of glubat, it can be combined with the mature wood production, cross-laminated timber (CLT) as CLBT or CLTB (Wen and Xiao 2023; Xiao et al. 2021).

The mechanical properties of bamboo-based are tested. Through quasi-static tests, Li et al. (2021) conducted the tension, compression, bending and shear tests for both thin-strip and thick strip glubat. A simple design-oriented axial stress-strain model was proposed, and strength values were calculated. The effects of loading directions on glubat materials were mentioned. The torsional behavior of thin-strip and thick-strip glubat was supplied by Wu et al. (2023), in which the properties were compared to a wood, spruce-pin-fir (SPF). The thin-strip glubat had better deformability with gentle degradation after peak loading compared with the thick-strip glubat and SPF specimens, attributed to its bidirectional bamboo fiber arrangement. To apply glubat material on construction industry, Li et al. (2019) researched the bending capacity of thin-strip and thick-strip full-scale glubat beams. The three-point bending tests on CLBT beams were conducted by Xiao et al. (2021), in which the SPF was used as the main ingredient in CLBT.

In addition to quasi-static performances, dynamic tests on bamboo- and wood-based materials are essential to understand their mechanical behavior under high-strain rate loadings. Chen et al. (2023) tested the impact bending characterizations of thin-strip and thick-strip glubat materials. The dynamic loading led to high uncertainty of glubat materials. The dynamic compression tests were conducted by Chen et al. (2024). The cross-aligned bamboo fibers helped the thin-strip glubat to suffer higher dynamic compressive capacities.

In this stud, the dynamic impact properties of glubat and SPF materials were studied by pendulum bending tests. The comparisons between glubat and SPF materials can help the optimization of CLBT materials, and provided the design parameters in engineering applications.

2. Experimental program

2.1. Materials

Glued laminated bamboo (glubat) (Xiao 2022; Xiao et al. 2013) is a multi-layer bamboo-based materials. Glubat has been manufactured from 3 to 5 years old moso bamboo (*Phyllostachys pubescens*), and phenol formaldehyde (PF) resin, using a two-step lamination process. A hot-pressure compression at ~5 MPa and 150°C initially was applied to combine the bamboo strips into boards. The industrial glubat panel dimension is about 2000 to 2500 mm in length, and 600 to 1200 mm in width. Two types of glubat can be defined on the thickness of the bamboo strips. One is thick-strip glubat, called G1, which used four layers of 7~8 mm thick, ~30 mm wide bamboo strip mats. The G1 specimens were normally heated via hot air at 175°C for industrial application. The thin-strip glubat, called G2, which was manufactured by gluing 15 layers of ~2 mm thick

bamboo strip in two orthogonal directions. The main bamboo fiber direction is longitudinal, and the ratio of main direction versus transverse direction is 4:1.

Considering the orthogonal properties, glulam panels can be employed to combine with cross-laminated timber (CLT), forming CLTB or CLBT hybrid panels (Wen and Xiao 2023). From CLT, spruce-pine-fir (SPF) is one of the most popular wood materials. The material of SPF was considered to compare with glulam. All the specimens were cut from glulam or CLT boards to the dimension of ~30 mm thick, in X-axis, 350 mm long, in Y-axis, and 30 mm wide, in Z-axis.

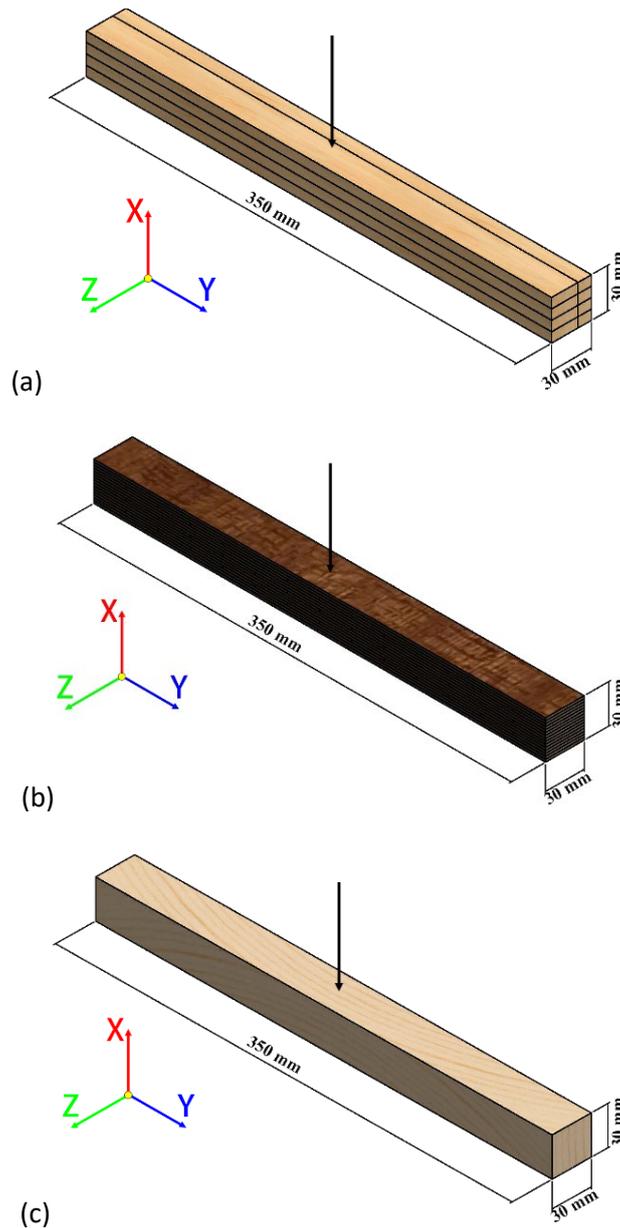


Figure 1. – Material types in this study: (a) thick-strip glulam, G1; (b) thin-strip glulam, G2; (c) spruce-pine-fir, SPF

To minimize the effects of moisture contents on bamboo- and wood-based materials, the specimens were controlled in the curing chamber (BPS-50CA Shanghai Yiheng, China). All the specimens were contained at an air-dried oven under 103°C for at least 48 hours, to ensure the mass keeping stable. The air-dried specimens were contained at the curing chamber under 20±1°C,

65±2% relative humidity (RH), for more than 14 days, until the specimens arriving at the equilibrium moisture contents. The moisture content of G1 was 4±0.5%, G2 was 6%±0.5%, and SPF was 9±0.5%. The detailed testing matrix was listed in Table 1. The effects of stressed surfaces were considered by two loading directions in X- or Z-axis, due to the anisotropic characterization of glulam materials. When the loading direction is in X-axis, the stressed surface was the surface of the specimen, and for Z-axis, the stressed surface was the interlayer side.

Table 1. – Testing matrix and specimen details

Materials	G1		G2		SPF
Loading directions	X	Z	X	Z	/
Numbers	5	5	5	5	5
Dimension	29.3×30.0×350.1		29.8×30.0×350.0		30.1×30.0×350.0
Moisture contents	4±0.5%		6±0.5%		9±0.5%

2.2. Pendulum impact test

The dynamic bending tests were conducted by a pendulum impact machine (Tianchen, China). Based on ASTM D3499 (ASTM 2019), ISO 13061-10:2017(International Standard 2017), GB/T 1927.17-2021(Chinese Standard 2021), the pendulum impact machine owns a semi-cylinder impactor and two semi-cylinder supports with the same diameter of 60 mm (Figure 2). The weight of impactor is 18.49 kg or 23.93 kg. The span length was 300 mm, as the specimen length of 350 mm.

The loading position was in the middle of the longitudinal orientation of specimens. The impact energy can be calculated by Eq. (1)

$$Q = wL(\cos A_1 - \cos A_2), \quad (1)$$

where Q represents the absorbing energy of a specimen in J;

w is the weight of the pendulum in kg;

L is the distance, from the axis of rotation to the center of mass, 0.937 m;

A_1 is the initial angle, in deg;

and A_2 is the final angle in deg. after the failure of the test specimen.

For G1 specimens, the applied pendulum hammer weight is 23.93 kg. For G2 and SPF specimens, the applied pendulum hammer weight is 18.48 kg. The initial impact angle was designed as 60°, implying the initial velocity is 3 m/s. The initial energy was designed as 110 J for G1, and 85J for G2 and SPF.

The impact toughness can be calculated by Eq. (2)

$$A_w = \frac{1000Q}{bh}, \quad (2)$$

where A_w is the impact toughness per specimen in kJ/m²;

b is the width of the specimen in mm;

and h is the thickness of the specimen in mm.

A lightweight accelerometer (DYTRAN Instruments, Inc) was equipped on the back of the pendulum hammer, measuring the acceleration and deceleration during the impact period. The acceleration was collected using a data acquisition system (National Instruments) with a sampling frequency of 25 kHz. The modulus of rupture can be calculated by Eq. (3)

$$\sigma_b = \frac{3P_m l}{2bh^2}, \quad (3)$$

where σ_b is the bending strength in MPa;

P_m is the maximum load in N;

l is the span length of the specimens, which is 300 mm.

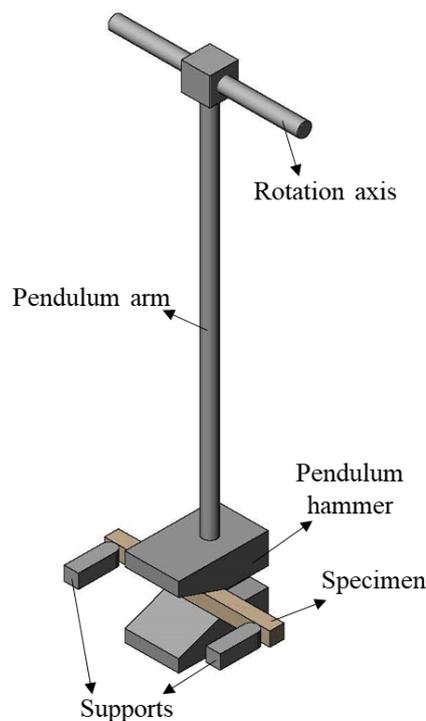


Figure 2. – Pendulum impact bending test schematics

3. Results

3.1. Failure modes

All specimens were destroyed after once impact in 10-15 milliseconds. The failure modes of typical G1, G2, and SPF specimens were shown in Figure 3. The effects of loading directions were significant on glubam materials, resulting that the G1-X (Figure 3 (a)) and G2-X (Figure 3 (c)) specimens demonstrated the delamination of gluing layers. The impact loading in X-axis implied extreme slides in layer to layer, that generated the high requirement of adhesive layers. When it comes to loading direction in Z-axis, more pull-out bamboo fibers appeared in the middle of specimens (Figure 3 (b), (d)). For glubam materials, the failure mode showed the characterization as splintering tension, showing interlaced cracks in the tension surface. For SPF material, the brash tension happened.

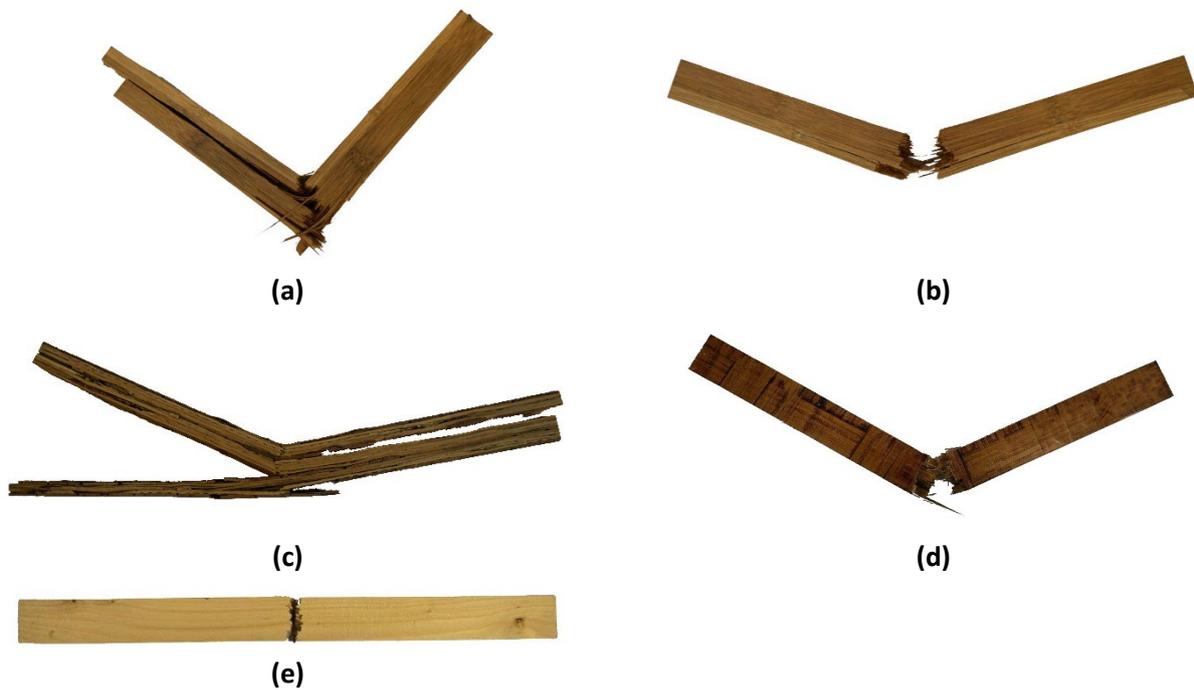


Figure 3. – Failure modes of typical specimens of (a) G1-X; (b) G1-Z; (c) G2-X; (d) G2-Z; (e) SPF

3.2. Impact toughness

Figure 4 shows the impact toughness, based on Eq. (2) from glulam and SPF specimens. The impact toughness values of G1 specimens were higher than those of G2 specimens, indicating that the G2 specimens owned more internal defects. The thin-strip manufacture of G2 specimens increased the utilized rate of raw bamboo, but led more potential defects in productions, consequently the decreasing of mechanical properties. The performances of impact toughness from G2 specimens showed better stability, in which the standard deviations kept smaller than the G1 values. The different loading directions influenced on the impact toughness performances of glulam. The loading direction in Z-axis would bring out slight reductions in G1 and G2 specimens. The different failure modes also explained the decreasing performances (Figure 3). The delamination in G1-X and G2-X led to the catastrophic damage, brought more absorbing energy during the impact. The tensile layers of G1-X and G2-X were entire bamboo strips. From the G1-Z and G2-Z side, the impact energy was digested by the fiber pull-out. The bamboo-adhesive interfaces had to suffer the impact loading, which was weakened than the entire bamboo strip layer. For SPF specimens, it is shown the lowest impact toughness behavior, indicating the application of bamboo-based materials was proposing to replace partial wood productions.

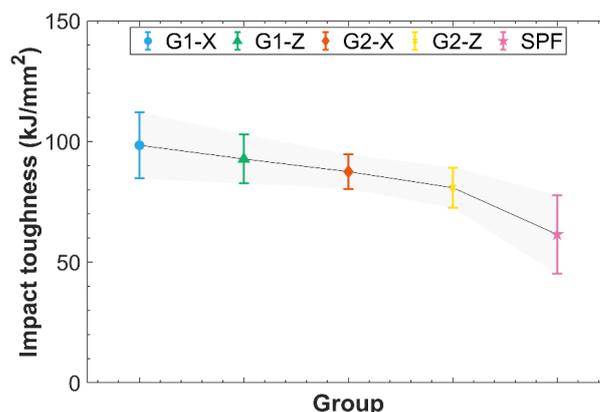


Figure 4. – Impact toughness from G1-X, G1-Z, G2-X, G2-Z, SPF

3.3. Modulus of rupture

Based on Eq. (3), the collective acceleration data can be used to calculate the dynamic modulus of rupture (MOR), shown in Figure 5. The dynamic MOR performed similar tendency as the behaviors of impact toughness in Figure 4. The G1 specimens had the better dynamic MOR than those of G2 specimens. The effect of loading directions became different on G2 specimens, where G2-Z demonstrated the higher dynamic MOR than those of G2-X. The stressed on interlayer side of G2 increased slightly. Compared to impact toughness, the impact forces were assessed by the accelerations, in which the high signal noises showed. The absorbing energies were collected from the pendulum machine, which contained the impact energy, possible frictional energy and mechanical losses. The accelerations were connected with only the impact energy, the differences of dynamic MOR tendencies might emerge. Under the impact loading, the G2-Z specimens increased the dynamic MOR from G2-X, exhibiting the orthogonal alignment of G2 materials strengthened the behavior. For SPF material, crucial standard deviations happened, and the average dynamic MOR was the minimum.

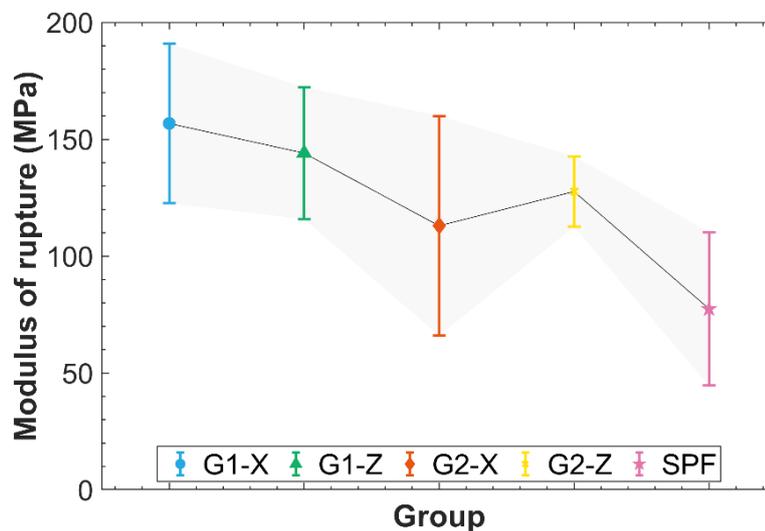


Figure 5. – Dynamic modulus of rupture from G1-X, G1-Z, G2-X, G2-Z, SPF

4. Conclusion

This research evaluated the impact bending behavior of glubam (G1 and G2) and SPF through pendulum tests. The experimental results revealed that the thick-strip glubam (G1) outperformed both the thin-strip glubam (G2) and SPF in terms of impact toughness and dynamic modulus of rupture, underscoring its superior energy absorption capacity and bending strength under dynamic loading conditions. The anisotropic characteristics of glubam were evident, as the loading direction significantly influenced the mechanical performance and failure modes. Loading along the X-axis induced interfacial delamination, absorbing more energy, whereas Z-axis loading resulted in bamboo fiber pull-out, leading to a slight reduction in mechanical properties. The study demonstrates the significant potential of glubam, particularly the G1 type, as a robust and sustainable construction material. The comparative analysis with SPF provides crucial design parameters for advancing the application of bamboo-wood hybrid composites, such as CLBT, in engineering structures subject to dynamic loads. Future work should focus on refining manufacturing techniques to minimize defects in thin-strip glubam and further exploring its long-term durability and performance in full-scale structural elements.

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